MAR10-2009-004689

Abstract for an Invited Paper
for the MAR10 Meeting of
the American Physical Society

Single particle to many-body physics in rotating optical lattices[1]

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Recent progress in creating artificial gauge fields for cold atom systems holds promise for experimental realization of many interesting models. In the presence of a periodic potential, the external gauge fields may be used to realize many lattice-gauge theories for the first time. We consider the simplest of such models, where an artificial magnetic field is coupled to the cold atoms and investigate various scenarios. Such an artificial magnetic field may simply be created by rotating the optical lattice, or by more elaborate means like light induced potentials. The physics of particles moving in a periodic potential in the presence of a magnetic field is rich, as it contains three parameters which control commensurate/incommensurate transitions. The first such parameter, flux quanta per plaquette of the lattice, controls the single particle physics. The energy spectrum as a function of this parameter is a fractal shape known as the Hofstadter butterfly. A second parameter is the number of particles per lattice site, which controls if certain insulating states like the Mott state are possible. The ratio of these two parameters give the filling factor, defined as the number of particles per flux quanta, which controls the quantum Hall physics. We first discuss the single particle physics where we investigate the relation between the Wannier functions and local ground states for each site. We show that the presence of the magnetic field requires a new definition of the Wannier functions, and these functions have large overlaps with local ground states. The Peirels substitution describes the hopping between sites faithfully for the lowest band. We also investigate how Peirels substitution has to be applied to higher bands such as the p- band, and discuss the resulting spectra. We then consider interacting Bosons in a rotating optical lattice and investigate the effect of the external magnetic field on the Mott Insulator- Superfluid transition. The phase boundary for this transition can be calculated exactly within mean-field theory and is shown to be controlled by the minimum eigenvalue of the Hofstadter butterfly. We argue that if one goes beyond mean field theory the Mott Insulator-Superfluid boundary is complex, and there are fractional quantum Hall phases of Bosons near every Mott lobe. As a third model we investigate the density profile for non- interacting fermions in a rotating optical lattice and find that the gaps of the Hofstadter butterfly are reflected as sharp plateaus in the density profile. Each one of these regions are topological insulators with quantized Hall conductivity. We argue that the Hall conductivity can be measured without any transport measurements, as the Streda formula relates Hall conductivity to the response of density to magnetic field change. Finally we investigate the physics of fermions with on-site attraction in a rotating optical lattice. We calculate the critical attraction strength for the transition from a topological insulator to a BCS superfluid. We also calculate the vortex lattice structures after BCS pairing takes place and investigate the transitions between different configurations of vortices.

[1]Supported by TUBITAK-KARIYER Grant no 104T165